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REDUCTION IN SOIL STRENGTH WITH INCREASE IN DENSITY

by Charles R. Foster

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REDUCTION IN SOIL STRENGTH WITH INCREASE IN DENSITY

by Charles R. Foster[1]

The usual concept of the relationship of soil strength with density is that an increase in density will result in an increase in strength. While this is generally true, the opposite occurs under certain conditions of moisture and density. This case is well illustrated in the laboratory California Bearing Ratio (CBR) tests when samples are compacted at a range of moisture contents and densities and then tested for CBR value. Figure 1 illustrates a family of curves of CBR versus density for equal moisture contents. This family was prepared from test results on samples compacted at three compactive efforts. The samples were compacted in five equal layers approximately 1 in. thick in 6-in.-diameter molds with the modified AASHO compaction hammer (10 lb, 18-in. drop). New material was used for each test. Figure 2(a) shows moisture-density curves for the three compactive efforts; figure 2(b) shows curves of CBR versus moisture obtained by running CBR tests on each of the compacted specimens. The CBR tests were made on the specimens as molded without soaking. The curves on figure 1 illustrate the same data shown on figure 2 interpolated to show families of curves of CBR versus density for equal moisture contents. This method of showing the results of CBR tests was developed in connection with the initial program of laboratory investigations of the CBR test (1)[2] conducted at the Waterways Experiment Station, Vicksburg, Mississippi, and has been used since that time in connection with CBR testing. This method is required by the Corps of Engineers in the design of flexible pavements (2).

It will be noted on figure 1 that the strength increases with an increase in density up to a certain point, and further increases in density result in decreases in strength. This condition occurs commonly in laboratory CBR tests and numerous families of curves showing this phenomenon have been presented in technical manuals published by the Waterways Experiment Station (3), (4), (5), (6). A paper by Eustis and McRae (7) contained families of CBR versus density for equal moisture contents. The authors called attention to the fact that CBR decreased with increase in density for high densities, but they did not discuss the subject in detail nor did they include a conclusion on this item. Families of curves showing this type of behavior have also been presented in an article by McRae and Turnbull (8), but the feature of a decrease in strength with an increase in density has received very little attention.

The results of unconfined compressive strength tests will also show a decrease in strength with increase in density at high densities. Triaxial test results will show this behavior if the deviator stress at a low percentage of strain is used; they do not show this behavior if the maximum or ultimate value of the deviator stress is used. Unconfined compressive strength and

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2. Numerals in parentheses refer to corresponding items in bibliography.

triaxial test results plotted in this manner are shown in the Waterways Experiment Station Technical Memorandums mentioned previously (3), (4), (5), (6), and were included in the paper given by Eustis and McRae (7).

Accelerated traffic testing accomplished at the Waterways Experiment Station on a test section with a test cart loaded to 120,000 lb produced similar results in the field. CBR measurements were made in the traffic lane before any traffic was applied and again after traffic had been applied. The measurements made after traffic were substantially lower than those made before traffic in areas where the moisture content was above a certain value. This behavior occurred with no significant change in moisture. Where the moisture content was below the certain value, the CBR increased with traffic. In all instances, the changes in strength conditions were accompanied by visible evidence in the behavior under traffic. Where decreases in strength were found, the pavement showed large deflections or weaving. Where increases occurred, the deflection was slight.

Unfortunately, the full importance of the conditions developing was not realized and the density values were not obtained for every case. As a result, development of a clear concept of the relationships between the behavior in the laboratory and in the field was not possible. The results of the tests are presented in detail in Waterways Experiment Station Technical Memorandum 3-312 (5). Pertinent data were extracted and presented by Redus and the author in a paper (9) in the symposium "Frost Action in Soils," Highway Research Board Special Report No. 2, and are not repeated here.

Subsequent to the tests described above, reductions in CBR have been noted in several of the accelerated traffic tests. In one particular series made in connection with investigations of landing mats, rather comprehensive measurements were made of CBR, moisture, and density following construction and at intervals during traffic. The purpose of these accelerated traffic tests was to determine if the landing mats would carry certain airplane wheel loads on a subgrade with a CBR of about 15 per cent. Detailed results are presented in Waterways Experiment Station Technical Memorandum 3-324 (6). Pertinent data are given in the following paragraphs:

The soil used in these studies was that native to the grounds at the Waterways Experiment Station. The material was obtained from the weathered zone of the loess found at Vicksburg, Mississippi. It is a silty clay with a liquid limit of about 38 and a plasticity index of about 13. The soil is classified as ML-CL by the Department of Army Unified Soil Classification System. The curves showing relationships between moisture, density, and CBR shown on figures 1 and 2 are for this soil.

The test sections were constructed in such a way as to provide a 24-in. depth of soil in as uniform a condition as possible. The soil was moistened, or dried, as necessary to obtain the desired moisture; placed in 6-in. lifts, and compacted with a heavy sheepsfoot roller. After construction of the subgrade was completed, the test area was surfaced with M6 (light steel), M8 (heavy steel), and M9 (aluminum) landing mat. The test sections were constructed under a hangar for protection from rainfall. The water table is at great depths (in excess of 100 ft) and was not a factor. The sections were covered with tarpaulins, except during the traffic period, to minimize evaporation.

Traffic was applied to the test sections with the load test cart equipped with airplane tires operated in a manner that simulated taxiway traffic. The cart traveled back and forth along the test section and was shifted laterally to produce uniform coverage across the traffic lane. One application of the tire over every spot in a traffic lane constituted one coverage. Traffic was con-

tinued until failure occurred or until 1,000 coverages had been applied. Observations of behavior were made throughout the period of traffic; and CBR, moisture, and density tests were made at pertinent intervals, particularly when significant distress occurred. Distress usually was evidenced by large deflections and weaving under traffic. Sections were rated as failed when a condition of mat breakage and surface roughness developed which was considered hazardous to aircraft operation. Failure was due primarily to shear deformation (plastic movement) of the soil under the repetitive loads. Table 1 summarizes the CBR, moisture, and density data and the behavior observations.

In the first group of tests (sections 1, 3, 4, and 5) it was intended to process the soil to an average moisture content in the range of 16.5 to 17.0 per cent and the results of the moisture tests made both before and during traffic averaged 16.9 per cent. As noted in table 1, the CBR during traffic was generally well below the intended value of 15 per cent and failures occurred well before the anticipated life of 1,000 coverages. In the second series of tests (sections 6, 7, and 8) the soil was processed to a drier moisture content to avoid the large reductions in CBR values that occurred in the first group of tests. The results of moisture tests made in these three sections before and during traffic averaged 14.7 and it can be seen in table 1 that instead of reductions in CBR, fairly large increases in CBR occurred. In the third group of tests (sections 9, 10, and 11), which were actually made for a different wheel assembly, advantage was taken of the preceding behavior and the soil was processed at a moisture content between the two preceding values. The results of the moisture tests made before and during traffic averaged 15.2 per cent. In this group of tests, the CBR during traffic was generally in the desired range and the tests were very successful in that all parts of the lane carried a substantial amount of traffic and some parts carried traffic for the intended life of 1,000 coverages. A detailed description of the behavior in section 10 is given as typical of the observations of behavior made in all of the sections.

Section 10 was 34 ft long and divided into two subsections, 10A and 10B, to accommodate slight differences in the manufacture of locking lugs of the M8 mat used for surfacing. It is believed that these differences in manufacture did not affect the behavior of the tests and the differences observed in behavior in different parts of the section were due to slight differences in moisture content of the subgrade.

Tests to determine the CBR, moisture, and density were made prior to traffic in a pit near the center of subsection 10B, which area was considered reasonably representative of the entire section. From two to five individual tests were made at three successive levels, usually 3, 10, and 17 in. below the surface of the subgrade. Table 1 shows the values obtained by averaging the individual tests at each level. The average moisture content prior to traffic throughout the three levels was 15.6 per cent and the CBR was 20 per cent.

As traffic was applied, it was noted that by 276 coverages large deflections were occurring in subsection 10B, and by 532 coverages the subsection was considered failed. The moisture content throughout the entire depth averaged 15.4 per cent, slightly lower than the as-constructed value (which probably represented evaporation), and the CBR was generally considerably lower than the as-constructed value of 20 per cent.

During this same period, subsection 10A carried traffic with no distress. In fact, subsection 10A carried traffic for almost the full intended life with no distress. In the west half of the lane of this subsection, relatively large deflections developed during the last few coverages but there was no sign of dis-

tress in the east half. In the west half of the lane, an increase in CBR was measured at 276 coverages, but by 686 coverages the CBR had dropped back to about the as-constructed value and by 1,000 coverages the values were considerably below the as-constructed value. By comparison, the CBR in the east half of the lane at the location measured at 1,000 coverages was very high. Average moisture contents in the east half were 15.0 per cent which is 0.4 percentage point less than the average of 15.4 per cent in the west half.

Similar observations and test data for the other sections are recorded in table 1. The next to last column in table 1 indicates whether or not the CBR decreased during traffic. A minus sign indicates a case where the CBR was less than the before-traffic value or less than a previous reading in the subsection at the same level. A plus sign is shown for all other cases. Since all the tests were not made at the same levels, it was necessary to plot curves of CBR versus depth in a few cases and interpolate values for intermediate depths. These curves are not shown in this paper.

Attempts were made to devise plots that would show graphically the increase in strength with increase in density up to a certain point and then the decrease with additional compaction. Figure 3 shows plots of field CBR versus density for equal values of moisture content similar to figure 1. Each of the individual diagrams on figure 3 shows the data for moisture conditions from 0.5 per cent below to 0.4 per cent above the even percentages of moisture indicated. The data for the individual ranges of moisture do not plot as a smooth progression of CBR versus density as obtained in the laboratory test, but such smooth progression cannot be expected in field tests. With the pattern of behavior known from the laboratory tests, it was possible to draw curves that were in reasonable agreement with the data. The solid symbols are pertinent to the part of the curve showing a decrease in CBR with increase in density as these are the cases where a decrease in CBR occurred during traffic. The curves were first drawn on work sheets for the individual ranges of moisture to best fit the points without regard to the curves in the other ranges. All the curves were then transferred to a single sheet and adjusted to give a smooth family of curves. The curves shown on figure 3 are the adjusted curves, and while in some individual plots the curves do not exactly agree with the plotted points on the individual diagram, the entire family represents a set of curves fitted to the data following the pattern set by the laboratory tests.

Figure 4 is a comparison of the curves of CBR versus density from the laboratory and field tests. The laboratory test results, shown by the dashed lines, were taken from figure 1; the field results, shown by solid lines, were taken from the various diagrams on figure 3. It can be seen that the field CB R values are consistently higher at equal values of moisture and density than the laboratory values. Whether the difference shown in these tests would have remained through periods of moisture adjustment (soaking in the laboratory test, and moisture accumulation in the field) is not known definitely as time would not permit allowing the subgrade to accumulate moisture in a normal manner, but data published by Redus and the author (9) indicate a fairly close agreement between the laboratory design CBR for a soaked sample and the value obtained in the field for this soil after five to seven years of moisture accumulation.

The decrease in strength above certain conditions of density in both the laboratory and field tests is believed caused by the development of pressure in the void phase of the soil structure. As long as the combination of moisture and density is such that no significant pore pressures develop, increases in

strength occur with increases in density. When pore pressures develop, further increases in density produce decreases in strength.

Attempts have been made to develop procedures to predict the moisture and density conditions where such a decrease will occur. In the laboratory tests, the moisture-density curves, as shown in figure 2(a), for three compactive efforts are usually arranged so that the peaks of the three curves (point of optimum moisture and maximum density) can be joined by a smooth curve which usually parallels the zero air voids line. This "line of optimums" is illustrated in figure 2(a). It has also been found that generally the moisture-density conditions along this "line of optimums" represent the points at which decreases in strength are indicated when the test data are plotted as curves of CBR versus density, as illustrated in figure 1. The first thought was that the CBR would decrease in the field at any time the density and moisture would fall above and to the right of the line of optimums (figure 2(a) and figure 5 is a plot made of the field moisture and densities from table 1 to show the relationship. The before-traffic data are not shown on figure 5 because they would only serve to confuse the picture. Laboratory compaction curves taken from figure 2(a) are shown on figure 5 for comparison.

It is noted on figure 5 that in general the solid points, which represent cases where the CBR decreased with traffic, tend to plot in a zone above the laboratory compaction curves, and the open points, which represent cases where an increase occurred during traffic, generally tend to plot below this zone. A few solid points occur below the zone and a few open circles fall in the zone. The reasons for these inconsistencies are not known but such inconsistencies are to be expected in field data. It was found that a curve of 3.5 per cent air voids separates the solid from the open points reasonably well. The curve of 3.5 per cent air voids falls slightly above and to the right of the laboratory compaction curve for the highest compactive effort. It has been found from other tests (3) that the field optimum moisture content, as developed by sheepsfoot and rubber-tired rolling, generally is wetter than the laboratory optimum (developed with the modified AASHO hammer) and for this specific soil has been found to range from 1 to 2 percentage points above the laboratory optimum. The curve drawn to indicate moistures and densities above which pore pressures in the field develop is at moisture contents about 1.5 to 1.7 percentage points higher than the curve representing the line of optimums for the laboratory compaction. It is believed that the curve drawn in figure 5 at 3.5 per cent air voids represents fairly closely the line of optimums for the compactive effort produced by the traffic. It is further believed that if a laboratory compaction test were available that duplicated field optimum, this test could be used to indicate moisture and density conditions above which decreases in strength could be expected to occur in the field.

A rather common occurrence in construction on silty type soils is the development of a soft, quaky condition under traffic of the construction equipment or during rolling operations. The condition can be controlled on fills by drying out the soil; or as has been demonstrated by Turnbull (10), a plastic condition can be produced deliberately where desired by rolling at moisture contents above optimum. The condition also occurs in subgrades during construction where the water table is high and is normally attributed to "pumping up of water from the water table." The development of extremely soft conditions in silty subgrades was observed by the author during the construction of Selman Airfield at Monroe, Louisiana, and Adams Airfield at Little Rock, Arkansas. The development of the soft, quaky condition was attributed to pumping up of water from the water table in reports which the author helped prepare on the airfields mentioned above. On reflection, it is believed that the

behavior in these two instances and probably in many more instances attributed to pumping up of water was nothing more than compaction to the point where the moisture and density were above the line of field optimums which resulted in large reductions in strength.

In summation, both the laboratory and field CBR tests indicate that a decrease in strength occurs when the moisture and density conditions are above certain values. This decrease in strength has been observed in many construction projects and has been confirmed by behavior in traffic tests. The traffic tests described in this paper emphasize that very small changes in moisture were critical in that strength increased at certain moisture contents and decreased at slightly higher values. The moisture-density conditions above which the decrease in strength occurs are defined in the laboratory by the "line of optimums," a curve drawn through the peaks of the laboratory moisture-density curves. The conditions appear to be defined in the field by the "line of optimums" for field rolling; the field line appears to lie at wetter moisture contents than the laboratory line. A laboratory compaction test which closely duplicates the field "line of optimums" probably could be used to predict conditions of moisture and density above which a decrease in strength would occur.

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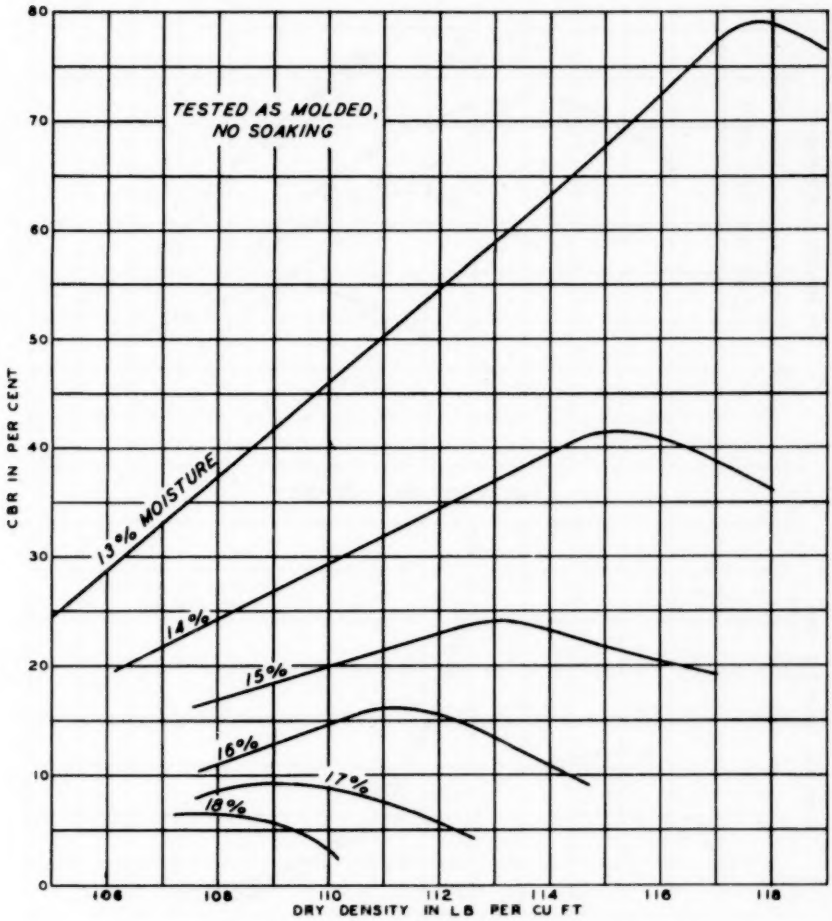
(9) "Moisture Conditions Under Flexible Airfield Pavements," by J. F. Redus and C. R. Foster. Published in Highway Research Board Special Report No. 2, "Frost Action in Soils," 1952.

(10) "Utility of Loess as A Construction Material," by W. J. Turnbull. Proceedings of The Second International Conference on Soil Mechanics and Foundation Engineering, Vol V, pp 97-103.

Table 1

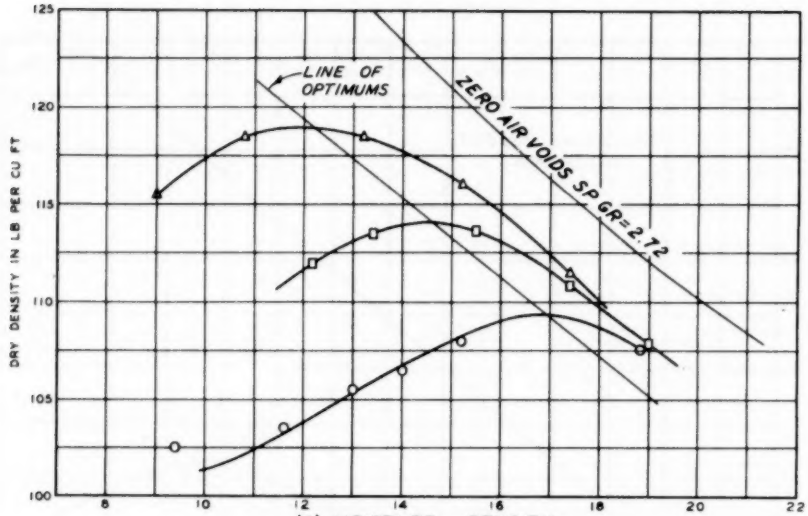
RESULTS OF TESTS AND OBSERVATIONS

Test Load	Section	Type of Mat	Depth In.	Before Traffic CBR	Before Traffic Moisture	Before Traffic Density	Subsection	Coverages	During Traffic Depth	During Traffic CBR	During Traffic Moisture	During Traffic Density	Change CBR	Behavior
80,000-lb dual wheels, 165 psi inflation pressure	1	MP	1	6	17.9	108.4	1A	12	3	14	17.0	112.5	+	Traffic stopped at 12 coverages
			5	12	17.5	109.0			8	6	17.2	112.9	-	
			13	11	16.1	112.7								
	3	MS	1	8	18.2	108.9	3A	108	2	8	15.9	115.5	-	Distress started at 40 to 50 coverages, failure
			5	21	16.5	109.8			10	7	16.3	114.7	-	occurred by 108 coverages
			10	17	16.5	110.2			19	5	17.5	111.8	-	
			13	17	17.0	111.6								
			17	11	17.8	109.8								
	4	MS	1-1/2	6	18.3	109.3	4B	192	3	9	15.9	115.7	-	Distress started at about 60 coverages, failure
			6	24	16.4	108.2			10	7	16.2	114.9	-	occurred at 192 coverages
			10	22	16.1	-								
			13	11	16.9	110.6	4A	204	2	15	15.2	117.5	+	Distress started at 120 coverages, traffic was
									9	13	15.8	115.9	-	stopped at 204, failure estimated at 230 cover-
									19	14	16.5	115.1	+	ages
	5	MP	2	7	17.8	109.1	5B	48	2	6	18.1	111.5	-	Distress started at about 50 coverages, failure
			8	14	16.8	112.1			9	3	17.6	111.8	-	occurred at 136 coverages
			15	10	17.9	111.7								
							5A	192	1	11	16.4	113.9	+	Distress started about 50 coverages, failure
									6	6	16.5	115.2	-	occurred at 192 coverages
									16	3	18.0	111.2	-	
	6	MS	1	19	14.4	107.0	6A	1000	2-1/2	67	14.6	114.8	+	Satisfactory at end of 1000 coverages
			8	24	14.7	107.3			10-1/2	46	14.3	109.6	+	
			17	26	13.6	108.1			19	24	15.8	111.7	-	
	7	MS	2	14	14.1	107.2	7B	1000	2	55	13.8	114.7	+	Satisfactory at end of 1000 coverages
			10	14	14.5	107.2			10	28	14.7	109.3	+	
			18	21	14.6	113.6			18	23	15.2	116.1	+	
	8	MP	3	17	14.4	106.9	8B	1000	3	48	14.5	116.4	+	Satisfactory at end of 1000 coverages
			11	13	15.1	103.9			11	34	15.6	112.4	+	
			19	13	14.0	109.1			19	18	16.4	113.1	+	
50,000-lb single wheel, 200 psi inflation pressure	9	MS	2	22	14.9	110.8	9B	250	4	12	14.8	118.3	-	Distress started at about 100 coverages, failure
			9	25	14.5	110.8			11	9	15.8	116.3	-	occurred at 250 coverages
			16	25	15.3	110.7			18	15	15.5	115.8	-	
							9A	276	4	14	14.5	118.9	-	Distress started at about 100 coverages, failure
									9	10	15.4	116.5	-	occurred at 276 coverages.
									16	27	15.2	116.4	+	
	10	MS	3	21	15.1	114.2	10B	276	3	13	14.9	118.5	-	Large deflections at 276 coverages
			10	20	16.5	113.2			10	12	15.4	117.2	-	
			17	19	15.2	113.3			17	14	15.4	115.7	-	
							5B2	4	4	15	14.5	117.1	-	Considered failed
									11	8	15.8	116.3	-	
									17	18	15.5	115.7	-	
							West half 10A	276	3	32	14.7	116.6	+	Satisfactory
									9	21	15.4	115.6	+	
									16	17	15.8	115.1	-	
								686	3	20	14.6	118.9	-	Satisfactory
									9	16	15.1	117.4	-	
									16	20	16.2	114.1	+	
								1000	3	18	14.5	119.5	-	Satisfactory almost to 1000 coverages but dis-
									13	11	15.9	116.5	-	tress apparent during last few coverages
									18	13	16.0	116.0	-	
							East half 10A	1000	3	51	15.5	117.0	+	Satisfactory
									10	43	14.5	116.2	+	
									17	30	15.1	113.7	+	
	11	MP	3	27	14.3	112.7	11B	276	3	29	14.5	118.2	+	Satisfactory
			9	25	15.3	111.9			9	37	14.9	111.0	+	
			18	20	16.0	110.2			18	26	15.8	110.3	+	
								670	3	68	13.5	119.3	+	Satisfactory
									9	29	15.1	117.1	-	
									16	25	16.2	113.7	-	
								950	3	19	14.3	118.3	-	Failed after 750 coverages
									10	10	15.5	117.2	-	
									17	21	15.9	114.8	-	
								1000-(Small area)	3	89	13.0	119.2	+	Satisfactory
									10	25	15.4	114.3	-	
									17	21	15.9	116.6	-	
							11A	900	3	15	14.2	118.9	-	Satisfactory to 750 coverages, distress apparent
									10	9	15.8	116.4	-	between 750 and 850 coverages, failed at 850 to
									17	14	15.9	116.2	-	900 coverages

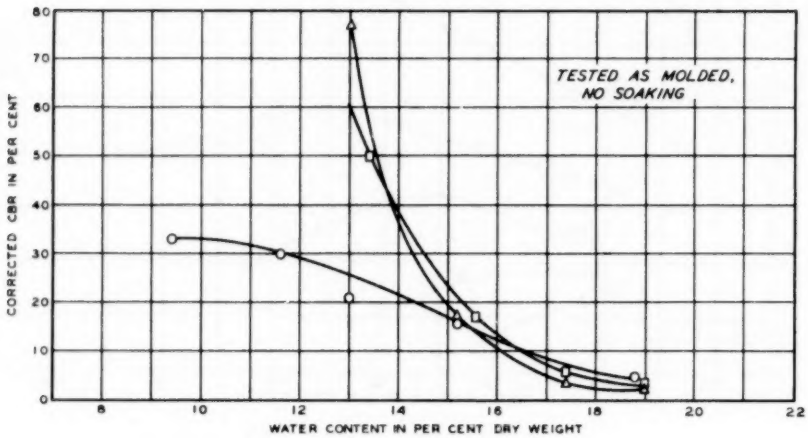


CBR VS DENSITY
FOR EQUAL MOISTURE CONTENTS
FROM LABORATORY TESTS

Fig. 1



(a) MOISTURE - DENSITY



(b) CBR VS MOISTURE

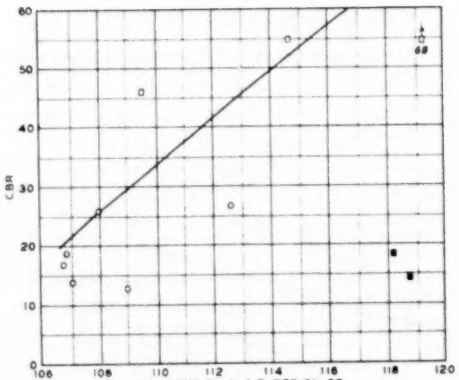
COMPACTIVE EFFORT

- ○ 12 BLOWS PER LAYER
- □ 26 BLOWS PER LAYER
- △ 55 BLOWS PER LAYER (MOD AASHO)

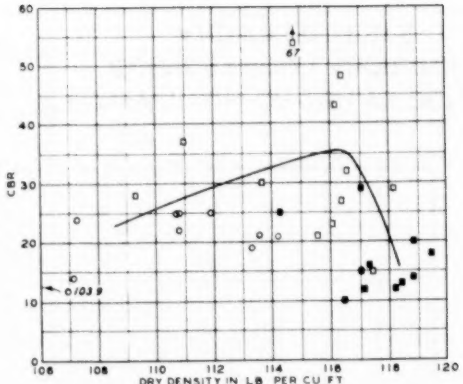
Fig. 2

LABORATORY MOISTURE, DENSITY, CBR TESTS

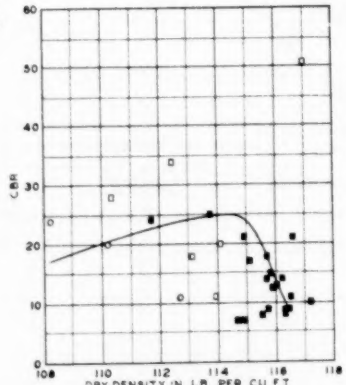
Fig. 3



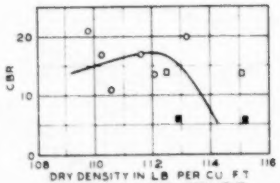
(a) 14% MOISTURE



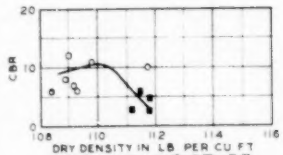
(b) 15% MOISTURE



(c) 16% MOISTURE



(d) 17% MOISTURE



(e) 18% MOISTURE

LEGEND

- ○ BEFORE TRAFFIC DATA
- □ DURING TRAFFIC DATA
- SOLID SYMBOL INDICATES CBR DECREASED DURING TRAFFIC

CBR VS DENSITY
FOR EQUAL MOISTURE CONTENTS
FIELD TESTS

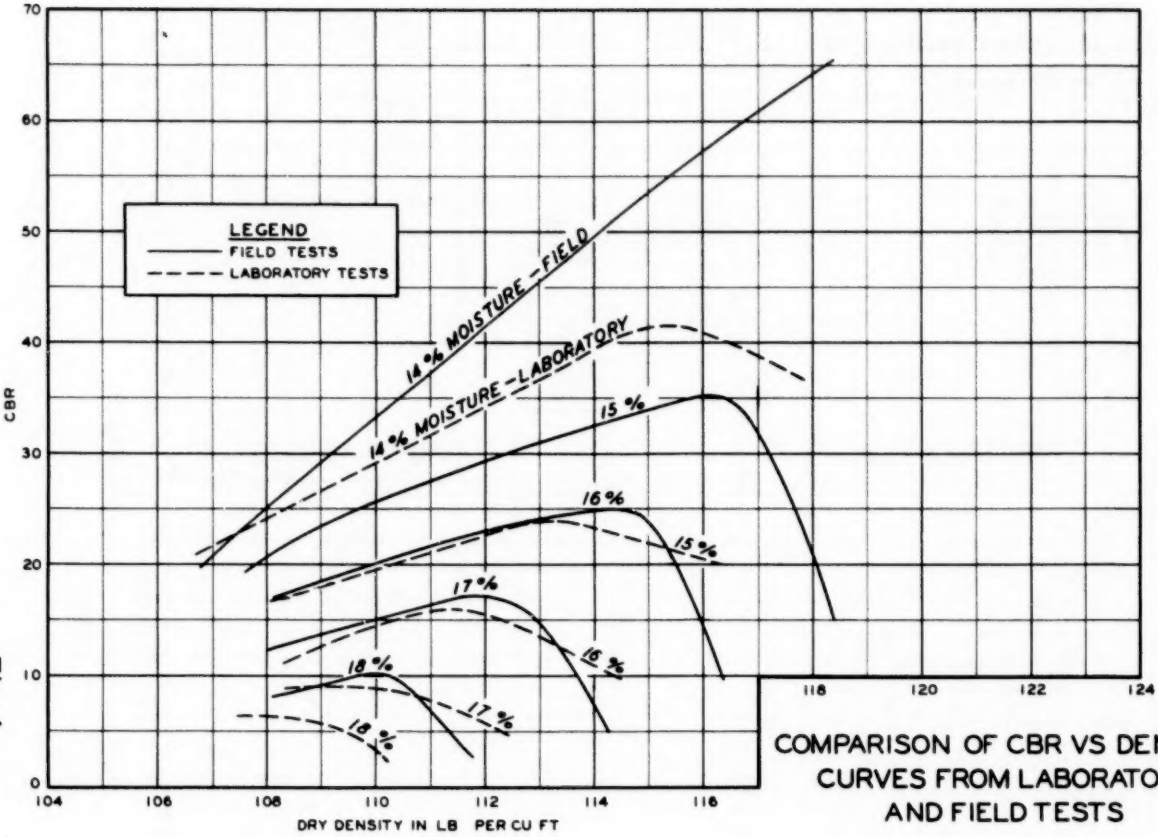


Fig. 4

COMPARISON OF CBR VS DENSITY CURVES FROM LABORATORY AND FIELD TESTS

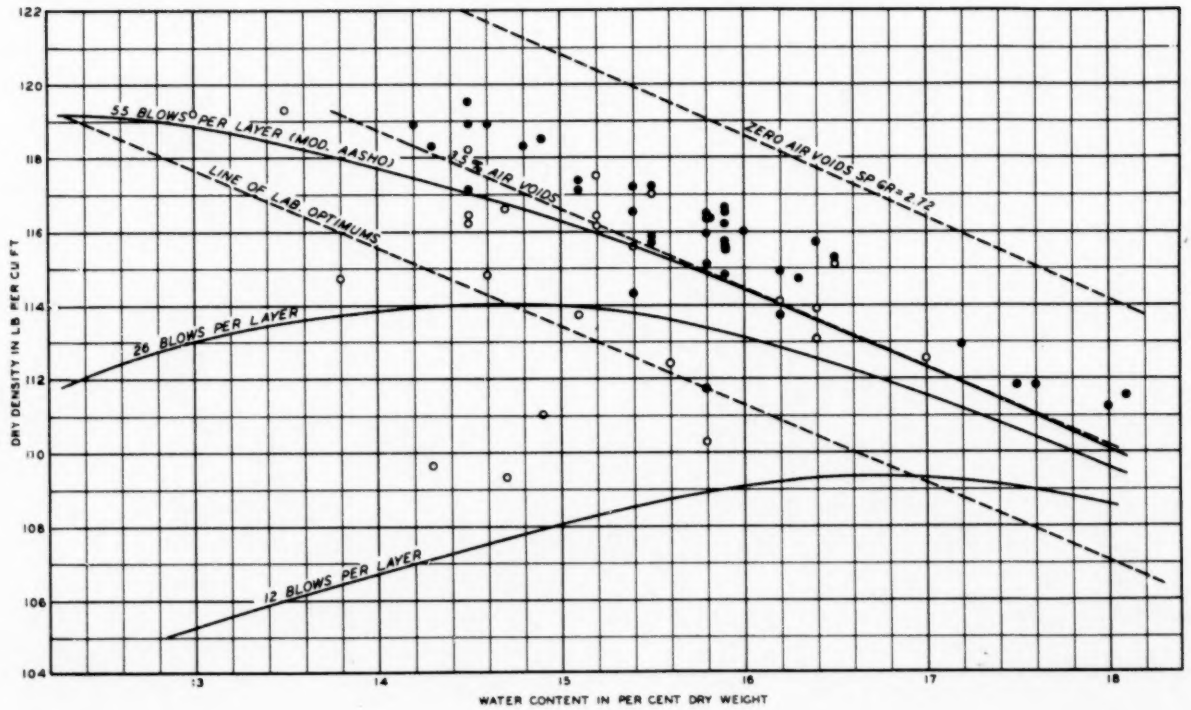


Fig. 5

LEGEND

● TESTS WHERE CBR DECREASED
○ TESTS WHERE CBR DID NOT DECREASE

MOISTURE - DENSITY PLOTS
FOR FIELD TESTS

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